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Overview of the Space Debris Environment

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There is a component of the space environment that is man-made pollution, termed "space debris;" it exists at all inclinations and, primarily, at altitudes of roughly 350 km to 2000 km. The size of this debris ranges from several meters to a fraction of a micrometer in diameter, and the particle distribution follows an inverse power law, with the smaller size component far exceeding that of the larger. Debris is composed primarily of alumina from solid rocket motor exhausts, aluminum from spacecraft structures, and zinc and titanium oxides from thermal control coatings. The accepted model of the space debris environment is that of Kessler et al., a complex model that predicts the number of particles that will impact a surface as a function of altitude, inclination, solar cycle, and particle diameter, as well as their collision velocities.

Recent data from LDEF has demonstrated both the accuracy and shortcomings of the Kessler model. Measured debris impactor fluxes are in good agreement with the model for ram surfaces. However, predictions of the model for other surfaces of a spacecraft are less accurate, most notably for the wake or trailing side. While the Kessler model is appropriate for long-term, average flux predictions, spatial-temporal impact fluxes measured on LDEF dramatically illustrated the presence of strong debris clouds that do not dissipate quickly in space and will encounter an orbiting spacecraft cyclically and repeatedly over its lifetime. LDEF data has also indicated the presence of debris in elliptical orbits, a fact not predicted by the Kessler model. This fact is responsible for the discrepancy between measured impact fluxes and predictions on trailing-edge surfaces.

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Preface

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Introduction

As a result of man's venturing into space, the local debris created by his presence now exceeds, at some orbital altitudes, that of the natural space meteoroid environment. This constant injection by man of this non-natural component, or space pollution, has accelerated due to the steadily increasing frequency of launches by the industrialized countries. There has for some time been a growing concern regarding the magnitude of this problem and its impacts, especially on the operations in space, current and future, and on the environment on earth. Indeed, this growing awareness of the potential unknown and known problems has led to efforts to mitigate this pollution problem on an international level[1].

Man's contribution to space pollution ranges from fuel residue to large derelict satellites weighing many kilograms. This debris population exists at many different altitudes and at all inclinations. As other countries become more active in space and if concepts such as those previously envisioned by SDIO are eventually deployed, it is inevitable that the growth of space debris will have to be dealt with and hopefully mitigated.

The problems associated with space debris can essentially be divided into four categories:

1. Effects resulting from reentry of space debris, i. e., earth impact.

2. Effects resulting from collisions of space debris with active spacecraft.

3. Effects of space debris with the environment, i. e., ozone depletion.

4. Effects of space debris on operations in space, i. e., surveillance, tracking, and communication.

Consideration of these presumably deleterious effects has prompted the Air Force to include in their Pollution Prevention Program a study of the environmental impacts of deorbiting space debris. One major aspect of this study is to assess the effect that deorbiting debris could have on the depletion of stratospheric ozone. Other aspects of this work include reentry risk assessments for earth impact of space debris[2] and the analysis of the effects of space debris on the continued military and civilian operations in space. The purpose of this study is to summarize the essential knowledge concerning the space debris environment, especially in light of the vast amount of new data that has resulted from retrieval and analysis of the Long Duration Exposure Facility (LDEF)[3].

This initial work is performed with a view towards defining the smaller-size component of this pollution since it dominates the debris population and is likely to have the most significant effect on atmospheric chemistry due to the large cumulative surface area that it presents. Additionally, from the point of view of atmospheric chemistry and/or ozone depletion, the debris environment in low Earth orbit (LEO) is of the most concern. Fortunately, the largest body of existing data and models is applicable to this orbit. LDEF has also provided new data that has increased our

understanding of the debris environment existing in high Earth orbits (HEO) or elliptical orbits. Since elliptical orbits generally have perigees below 400 km, debris in these orbits would most certainly also have effects on the atmosphere. In fact, many highly inclined elliptical orbits have, by design, their perigees over the south polar region, and ozone depletion has already been detected in this area. Future studies will focus on the specific hazards associated with space debris, such as collision with spacecraft and the ensuing damage.

Background

Two major components exist within the dynamic space environment; namely, natural meteoroids from within and outside the solar system and man-made debris dating back to the onset of space exploration in 1957. Space debris is the man-made material left in space as a result of our space activity. It ranges in size from microscopic particles of rocket propellants, to fragments created during explosions and collisions in space, to large spent rocket motor cases or even derelict satellites. Some debris has escaped the Earth's gravity or re-entered the Earth's atmosphere, but much has been left in orbit about the Earth. That debris still in orbit about the Earth is of concern as a potential hazard to spacecraft. The larger pieces are of even more concern with respect to reentry and eventual Earth impact. These large pieces of debris are tracked with radar and ground telescopes and cataloged. Meteoroids arrive at the Earth from almost all directions; some are in orbit around the sun, some are in hyperbolic paths leaving the solar system (β-meteoroids), and some are from outside the solar system. The debris is in both near-circular and elliptical orbits around the Earth. Although both types of particles exist all the way out to geosynchronous orbits (GEO), the major populations of debris are within the altitude range of 350–2,000 km.[4,5]

It is estimated that there are about 3,000,000 kg of man-made orbiting objects within about 2,000 km above the Earth's surface. Most of this mass is due to approximately 3,000 spent rocket motor cases, inactive payloads, and a few active payloads. These objects are mostly in high-inclination orbits and sweep past one another at a relative average speed of 10 km/s, roughly half the speed of meteoroids. A smaller mass, approximately 40,000 kg, is in the remaining 4,000 objects currently being tracked by U. S. Space Command radars. Most of these objects are the result of more than 100 on-orbit satellite fragmentations. The first satellite explosion was observed by NORAD radar in 1961. Investigation of this phenomenon has intensified greatly since then to increase knowledge of the space debris population below the 10-cm-diameter detection limit for radar. It is now estimated that the detection limit for radar approaches 1-cm diameter. Recent ground telescope measurements of orbiting debris, combined with analysis of hypervelocity impacts on returned surfaces of the Solar Maximum Mission (SMM) and the Long Duration Exposure Facility (LDEF) satellites, indicate a total mass of approximately 1,000 kg for orbital debris sizes of 1 cm or smaller and approximately 300 kg for orbital debris smaller than 1 mm. The significant difference between the orbital-debris population and the meteoroid population is that most of the debris mass is found in objects several meters in diameter, rather than 0.1 mm in diameter for meteoroids. This large reservoir of mass may be thought of as a potential source of particles in the 0.1 to 10 mm range. This distribution of mass and relative velocity is sufficient to cause the orbital debris environment to be more hazardous than the meteoroid environment to most spacecraft operating below 2,000 km. As of July 1992, there were a total of some 7,000 objects in orbit tracked and cataloged by the United States Space Command, with only 2056 classified as payloads.[6,7]

Debris population distribution is largely a function of launch frequencies and sites, with subsequent perturbations caused by accidental or deliberate explosions, collisions, fragmentations, surface erosion, and manned or unmanned mission-related debris. These latter perturbations include ejected lens covers, explosive bolts, and waste dumps from the Shuttle. Currently, the greatest

concentration of debris occurs at inclinations toward the pole of 60°, 80°, and 100°. While debris in LEO exists from about 350 to 2,000 km, the highest concentration appears to be near 1,000 km. Once the debris is created, differential precessions will cause the initial cloud of debris to form a toroid, or belt, around the Earth with holes near the pole.[8,9,10] Consequently, the flux of particles that could impact a spacecraft is a function of the latter's inclination and altitude, and the resulting impact velocities can range from zero to about 16 km/s for near circular orbits, or to about 19 km/s for highly elliptical orbits such as Hohman transfer orbits out to GEO.[4]

For both meteoroids and debris, the particles can range in size from sub-μm to many centimeters. However, both components display an inverse power law of number versus size with the smaller particles being far more numerous than the larger ones. Mathematical modeling of this distribution of orbital debris predicts that collisional fragmentation will cause the amount of mass in the 1 cm and smaller size range to grow at twice the rate as the accumulation of total mass in Earth orbit. Over the past 10 years, this total mass accumulation has increased at an average rate of 5% per year, indicating that the small sizes should be expected to increase at roughly 10% per year.[4,6]

Debris Environment Model

The accepted model of the space-debris environment is that of Kessler, Reynolds and Ans-Meador: "Orbital Debris Environment for Spacecraft Designed to Operate in Low Earth Orbit," also known as "the Kessler model."[11] Recently, this model was updated (June 1991) and is now known as the "revised Kessler model," or "Space Station Freedom Natural Environment Definition for Design," NASA Document SSP 30425 Revision A.[12] According to this model, the cumulative flux of orbital debris of size d and larger on a randomly tumbling spacecraft or surface orbiting at an altitude h, inclination i, in the year t, when the solar activity for the previous year was S, is given by the following equation:

$$F(d,h,i,t,S) = H(d)\Phi(h,s)\Psi(i)\,[F_1(d)g_1(t) + F_2(d)g_2(t)],$$

where

F = flux, in impacts/m^2/year

d = orbital debris diameter, in cm

t = time, in years

h = altitude, in km $(350 < h < 2000)$

S = 13 month smoothed 10.7 cm wavelength solar flux for year t-1, in 10^4 Jy,
$1\ \text{Jy} = 10^{-26}\ \text{W m}^{-2}\ \text{Hz}^{-1}$

i = inclination, in degrees

$H(d) = [10 \exp(-(\log_{10}d - 0.78)^2/0.637^2)]^{1/2}$

$\Phi(h,S) = \Phi_1(h,S)/(\Phi_1(h,S) + 1)$

$\Phi_1(h,S) = 10^{(h/200-S/140-1.5)}$

$F_1(d) = 1.22 \times 10^{-5}\, d^{-2.5}$

$F_2(d) = 8.1 \times 10^{10}\,(d + 700)^{-6}$

$g_1(t) = (1 + q)^{(t - 1988)}$ for $t < 2011$

$g_1(t) = (1 + q)^{23}\,(1 + q')^{(t - 2011)}$ for $t > 2011$

$g_2(t) = 1 + p\,(t - 1988)$

where

q and q' = the assumed annual growth rate of fragments in orbit, q = 0.02, q' = 0.04

p = the assumed annual growth rate of mass in orbit, = 0.05

The function Ψ (i) = the inclination dependence of the flux; for an inclination of 28.5°, the value of Ψ (i) is 0.91.

An average 11-year solar cycle has values of S that range from 70 at solar minimum to 150 at solar maximum.

Figure 1 shows an application of the model for a 500-km, 30° inclination orbit with t = 1995, and S = 97. The corresponding model used for the prediction of meteoroid fluxes is also shown for comparison. Some discussion regarding this model is warranted.[13]

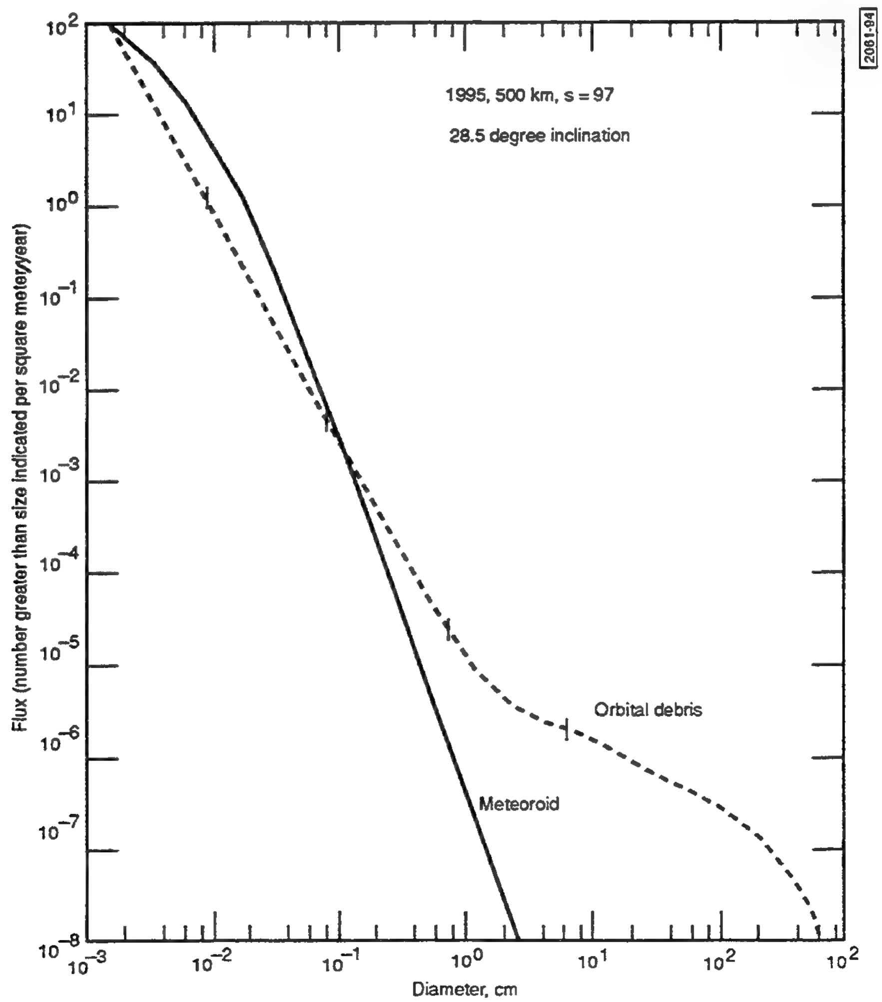

Figure 1. Comparison of meteorid and orbital debris fluxes as a function of size.

The Kessler model assumes that all debris particles are in circular orbits and, therefore, have a speed in common with that of any spacecraft co-located in the same orbit at the same altitude. This logic immediately implies that impacts can only be in the plane parallel to the Earth's surface. Therefore, on an oriented, non-spinning spacecraft, there will be no impacts on the trailing or wake side of the spacecraft. Similarly, the model predicts that there will also be no impacts on the earth-facing or anti-earth-facing (space) ends. Therefore, only the ram and sides of a spacecraft can be hit. Figure 2 shows a comparison of the predictions of this model (and the corresponding meteoroid model) for the ram or leading side of LDEF with experimental data.[13]

The debris model presupposes that the number of impacts per unit area are functions of the 11-year solar cycle, altitude, inclination, particle size, and time. A growth model has been assumed that has two components; namely, that due to launches and that due to fragmentation. The model has the functional form that is the product of four factors.[13]

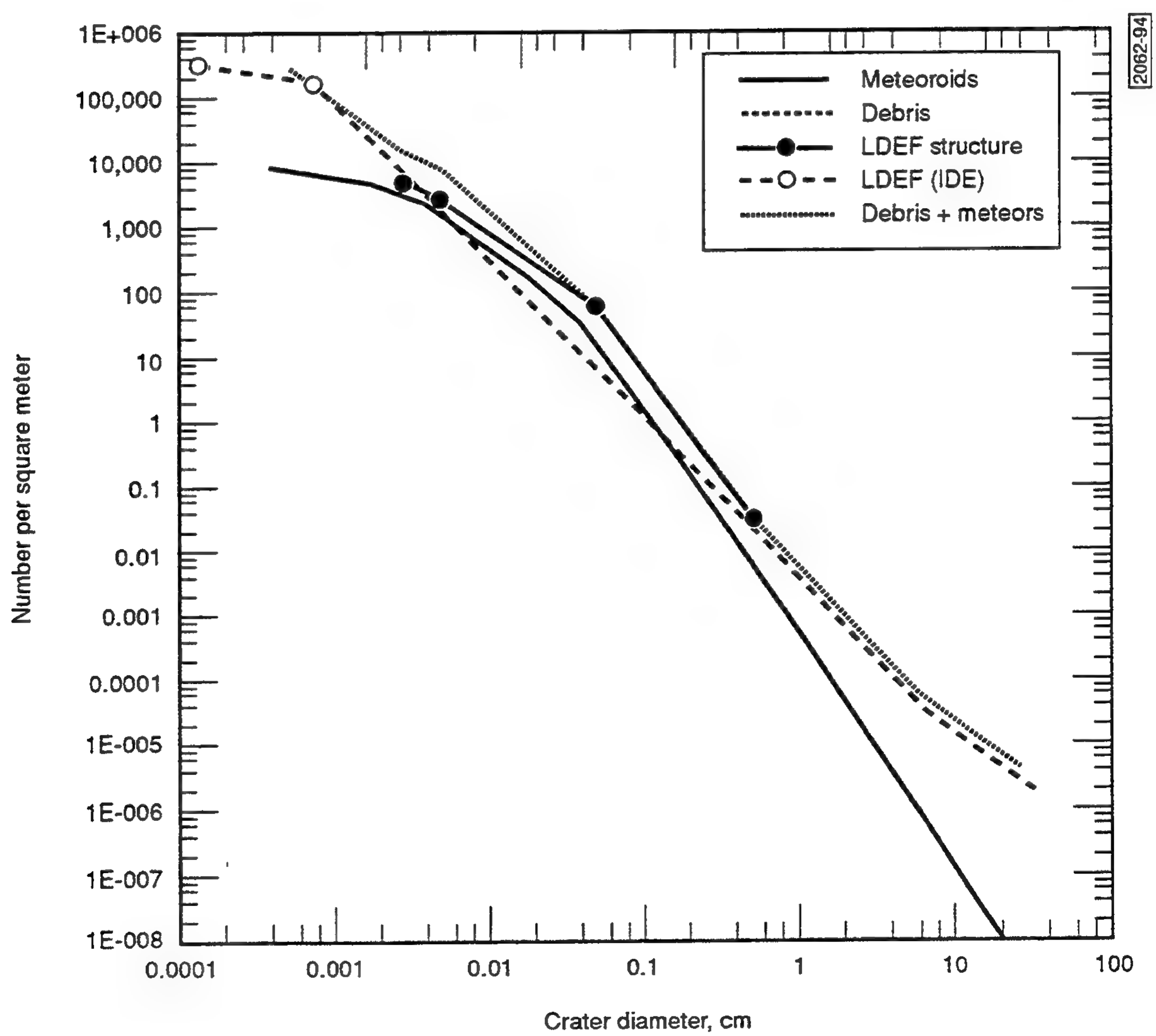

Figure 2. Comparison of LDEF data to model predictions. Ram direction; 5.75 years exposure (from Ref. 13)..

The factor Φ is essentially a time integral for the model being composed of two parts: the previously mentioned escalation terms and a function of altitude and solar activity. The function Φ_1 is a parameter based on altitude and solar activity. Because the solar cycle varies within an 11-year period in a sinusoidal manner, there is a corresponding time dependence to this function.

The factor Ψ is a function given by Kessler that describes the relative number of impacts seen by a spacecraft as a function of inclination. As shown in Figure 3, this function has two maxima: one in the neighborhood of 80° inclination and the other near 100°. These maxima occur because of the large number of near-polar missions that have been launched, especially sun-synchronous ones that are just beyond 90°.[13]

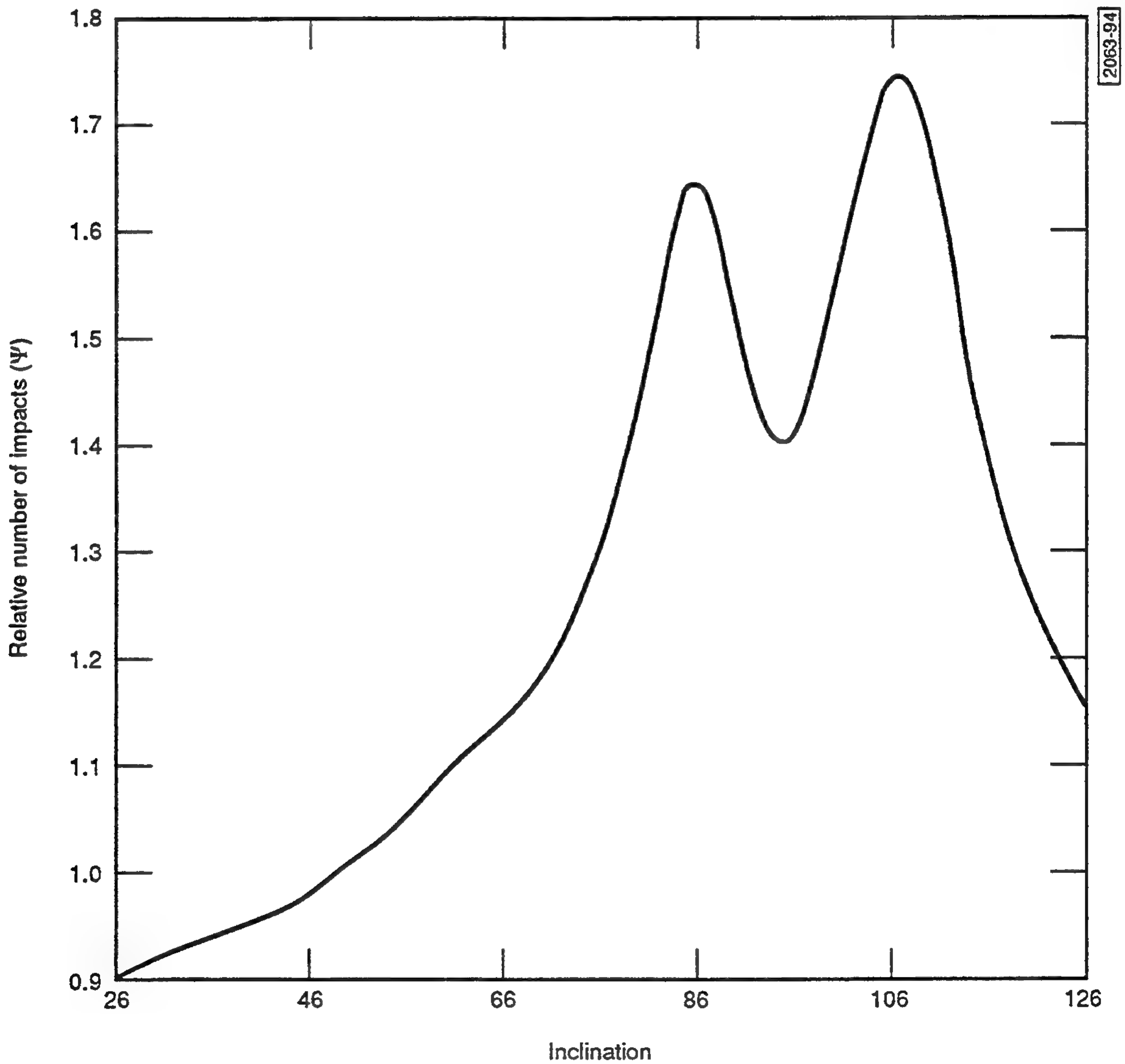

Figure 3. Flux dependency on inclination.

The F function is a cumulative, size-dependent function that increases rapidly as the size of the debris particle decreases with an inverse power of 2.5. There are two growth factors: one describing the small debris particles and one describing the large ones, with the break point being about 1 cm. The small particles are assumed to escalate according to a binomial function and are increasing at a compound rate of approximately 2% per year. The larger particles are assumed to escalate linearly at a rate of roughly 5%. These two rates are based on trends of past existing data and reasonable assumptions for future space activities (as seen by Kessler). The projected range of activities is shown in Figure 4. The relative use of different orbits is assumed to remain constant. For example, the history of launches by the former USSR has been such that 80% of their

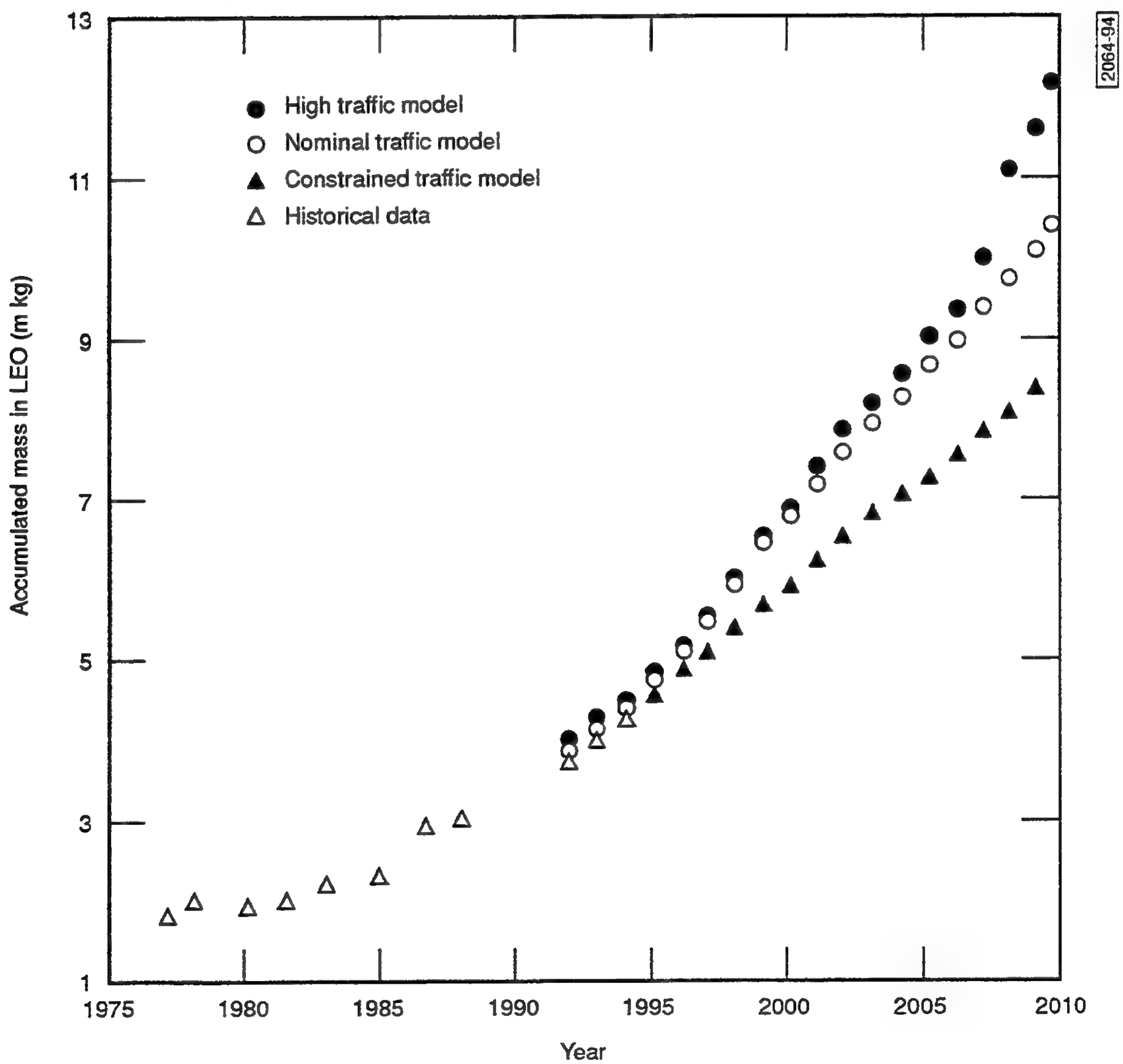

Figure 4. Projected growth of accumulated mass in LEO.

payloads re-enter within two years of launch and, consequently, do not contribute significantly to the debris environment. If this changes, and higher, longer-life orbits are used, the population of objects in LEO would grow at a proportionately increased rate. It is also assumed that efforts to minimize fragmentation of satellites in orbit will continue such that these events will continue at a rate of only one per year. In the last decade, intentional, or apparently intentional, fragmentation of satellites accounted for 71% of the known fragmentation events. An important short-term factor not included in the model is the flux arising from the unintentional or inadvertent fragmentation of a satellite. In the region of such a breakup, an enhanced flux may be apparent for a considerable period of time, depending on the altitude of the breakup and the size and velocity distribution of the resulting debris. Analysis of such an event indicates that the debris flux could be increased by factors of a few tens of percent for a year or more. As a possible worst-case extreme, a factor of 4 increase could result.[13]

When all these factors are combined, plots like the one in Figure 5 can be generated.[13] This figure indicates the dependence of the debris flux on solar activity and altitude. This plot gives the cumulative debris flux for particles greater than 0.1 cm in diameter from the period of 1985 to

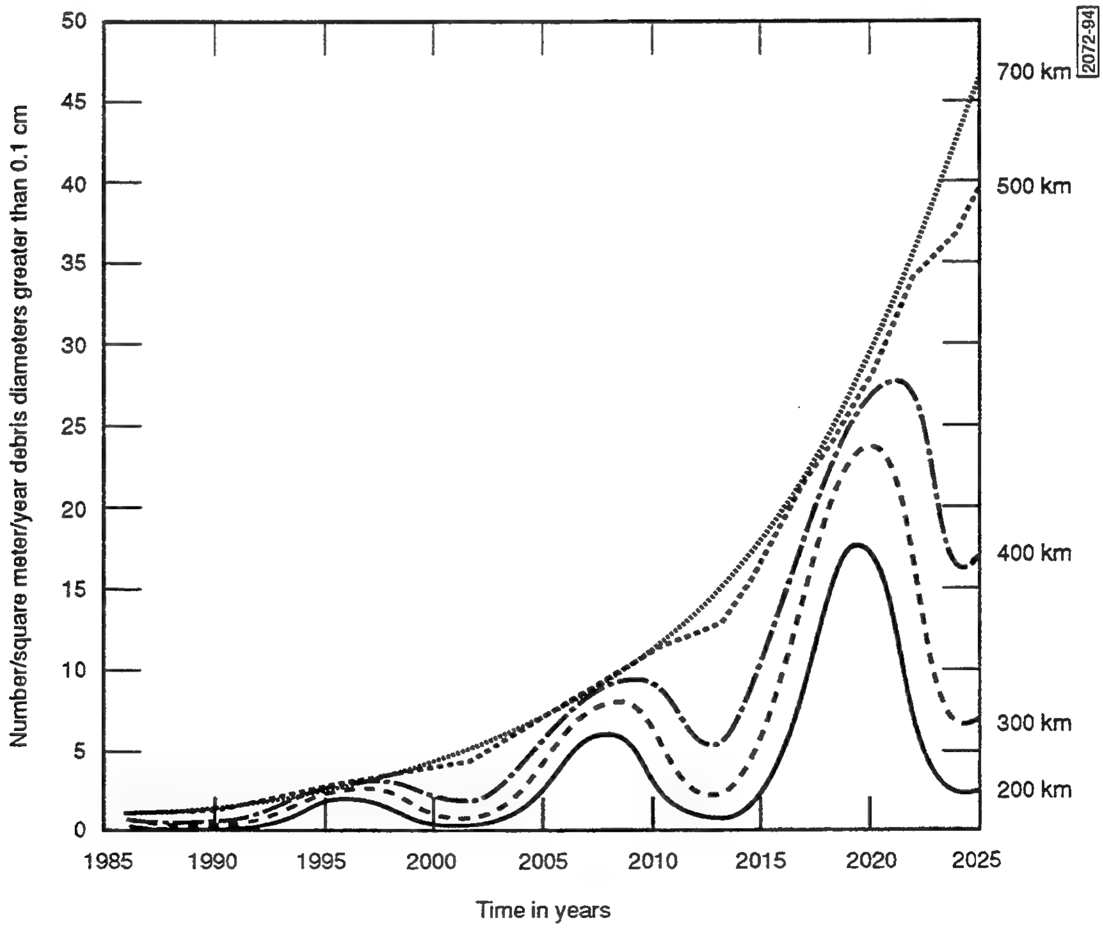

Figure 5. Dependence of debris flux on solar activity and altititude (from Ref. 13).

2025. An important point to note from this figure is that for debris at altitudes greater than 700 km, there is only a simple growth factor since the effects of the atmosphere are negligible. However, as altitude decreases below 700 km, the effect of atmospheric heating as a result of the cyclical solar activity becomes evident.

The Kessler model as discussed above presupposes that there is a given function (the F function) that describes the flux of particles versus particle diameter that can be scaled up or down according to such factors as inclination, altitude, and total time. The function does not include any size-dependent differential skewing effects due to aerodynamic drag even though aerodynamic drag is responsible for the time dependence of the particle fluxes due to the solar cycle since this causes atmospheric expansion and contraction. It is well known, however, that the lifetime of an orbiting body in LEO depends strongly on the overall mass-to-area ratio (M/A). Kessler has provided a plot, shown in Figure 6, that gives the typical lifetime of an average spacecraft as a function of the initial altitude and phase of the solar cycle. This average body had a M/A of

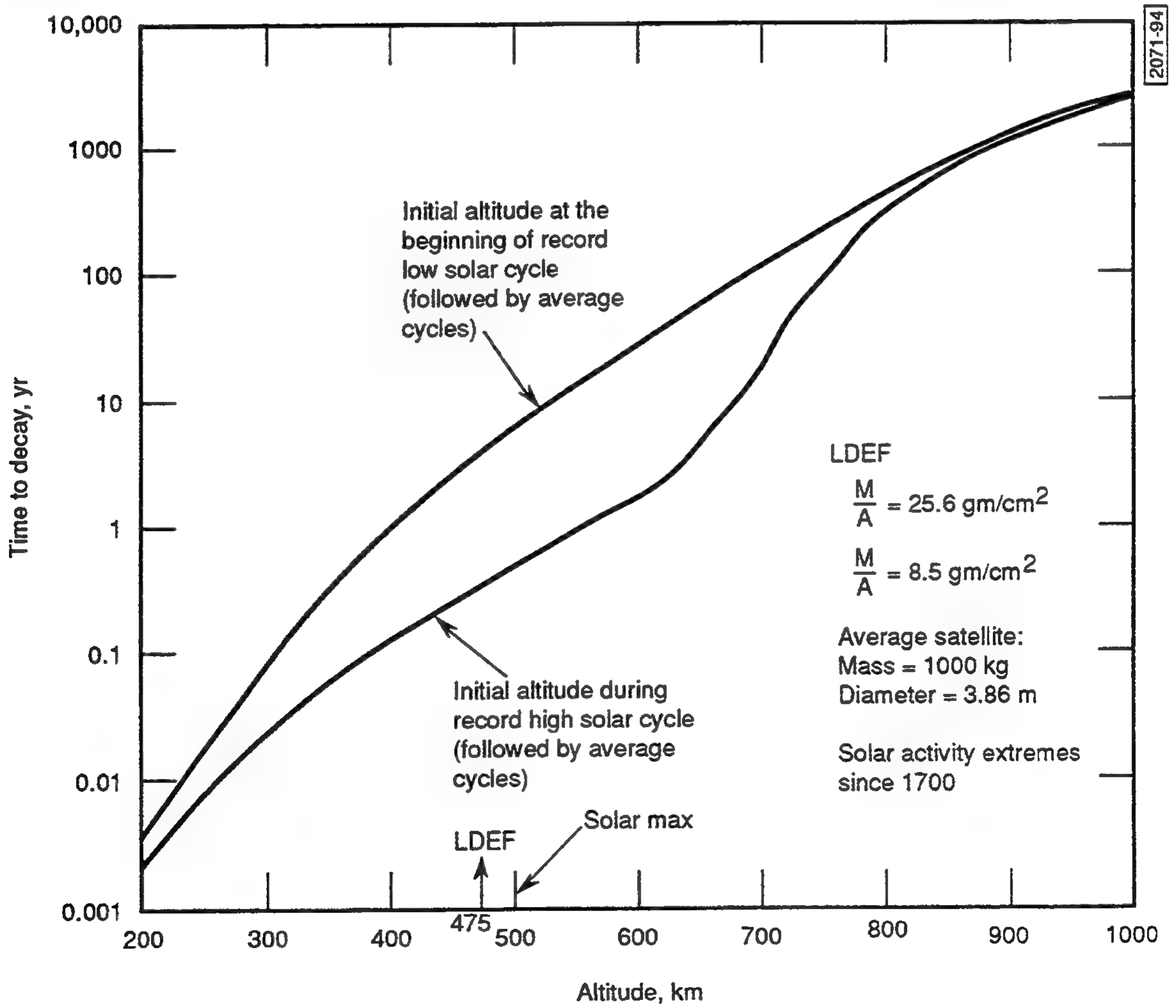

Figure 6. Extremes of average satellite lifetimes due to solar activity—circular orbit.

about 8.5 g/cm^2. Interestingly, Kessler's data indicates that LDEF, with an initial altitude of 475 km and an M/A of 25.6 g/cm^2, should have remained in orbit for approximately six years. The actual time was very close to 5.75 years. If we apply this same logic to other debris, we would predict that µm-sized particles would remain in space for very much shorter periods of time at the same altitude. Actually, below 1 µm in size we would expect the natural decay period to be sufficiently short such that the particle would de-orbit in a matter of hours, or after a few orbits. This argument implies that there should be a skew to the particle distribution such that the flux of small particles is a strong function of the initial altitude at which the debris was formed. Thus, at lower altitudes, the flux of small particles should reduce below that seen at higher altitudes.[13]

Orbital Debris Collision Velocity

For bodies in LEO, whether orbital debris or satellites, there is only a small change in speed versus altitude even out to 2000 km, and the average speed is about 7.7 km/s (at 500km). However, because different objects are in different orbits, collisions are possible with impact speeds between zero and 15.4 km/s, with an average speed of about 10 km/s. The actual collision velocity is dependent on the angle between the velocity vectors, and is independent of object size and mass. In order to calculate the directionality of the debris impacts and their velocity distribution, one uses Kessler's velocity function.[6,11] This function, f (v), describes the relative number of debris impacts between collision velocity v and v + dv. Averaged over all altitudes, the non-normalized collision velocity distribution relative to a spacecraft with orbital inclination i is given by the following:

$$(v) \;=\; (2vv_o - v^2)\;(G\exp[-((v - Av_o)/(bv_o))^2] + F\exp\;[-((v - Dv_o)/(Ev_o)) + HC\;(4vv_o - v^2),$$

where v is the collision velocity in km/s, A is a constant, and B, C, D, E, F, G, H, and v_o are functions of the orbital inclination of the spacecraft. The values of these constants and parameters are as follows:

$A = 2.5$

$B = 0.5$	$i < 60$
$0.5 - 0.01\ (i\text{-}60)$	$60 < i < 80$
0.3	$i > 80$

$C = 0.0125$	$i < 100$
$0.0125 + 0.00125\ (i\text{-}100)$	$i > 100$

$D = 1.3 - 0.01\ (i\text{-}30)$

$E = 0.55 + .005\ (i\text{-}30)$

$F = 0.3 + 0.0008\ (i\text{-}50)^2$	$i < 50$
$0.3 - 0.01\ (i\text{-}50)$	$50 < i < 80$
0.0	$i > 80$

$$G = \begin{cases} 18.7 & i < 60 \\ 18.7 + 0.0289\,(i-60)^3 & 60 < i < 80 \\ 250.0 & i > 80 \end{cases}$$

$$H = 1.0 - 0.0000757\,(i-60)^2$$

$$v_0 = \begin{cases} 7.25 + 0.015\,(i-30) & i < 60 \\ 7.7 & i > 60 \end{cases}$$

When f(v) is less than zero, the function is set to zero. Plotting this function for various inclinations, we can generate a family of curves. These are shown in Figures 7 and 8. The Kessler velocity distribution essentially includes a double Gaussian. For zero inclination parallel to the equatorial plane, the function shows a broad distribution resembling a single Gaussian centered at about 11 km/s. However, as the angle of inclination increases toward 180°, the function first splits into two Gaussians and then gradually narrows to a single large peak near the maximum collision velocity of 15.4 km/s.[13]

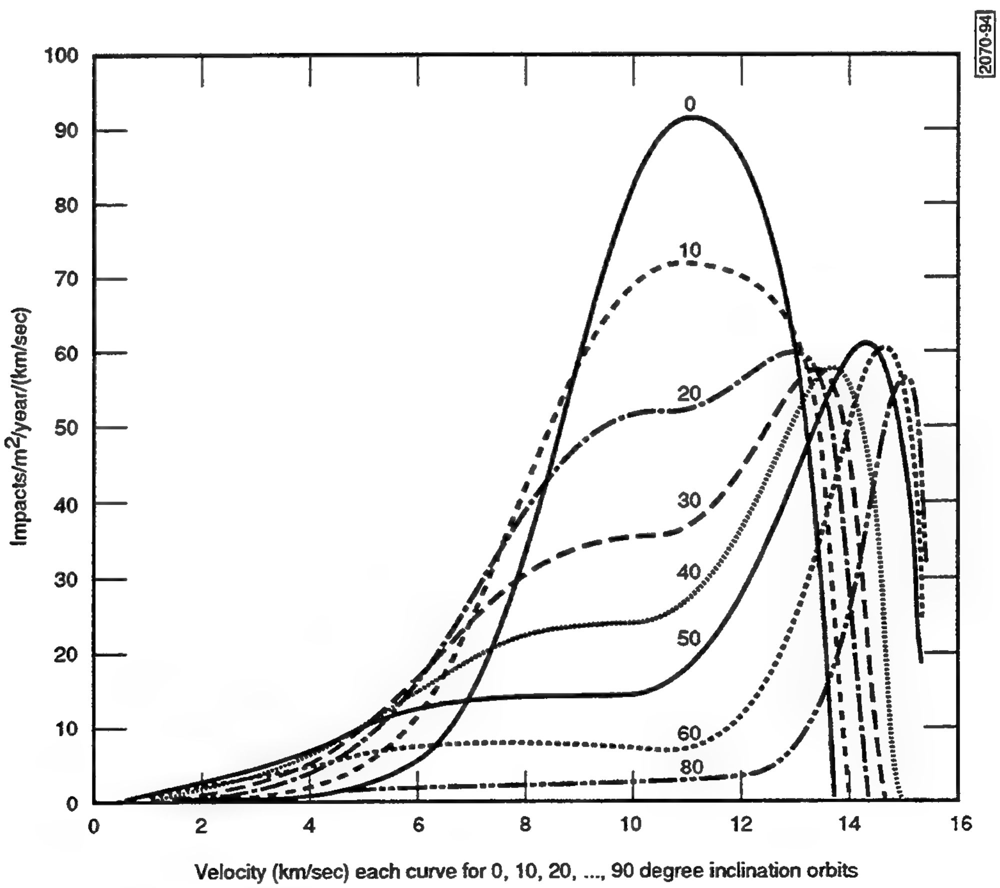

Figure 7. Kessler velocity function, f(v), (from Ref. 13).

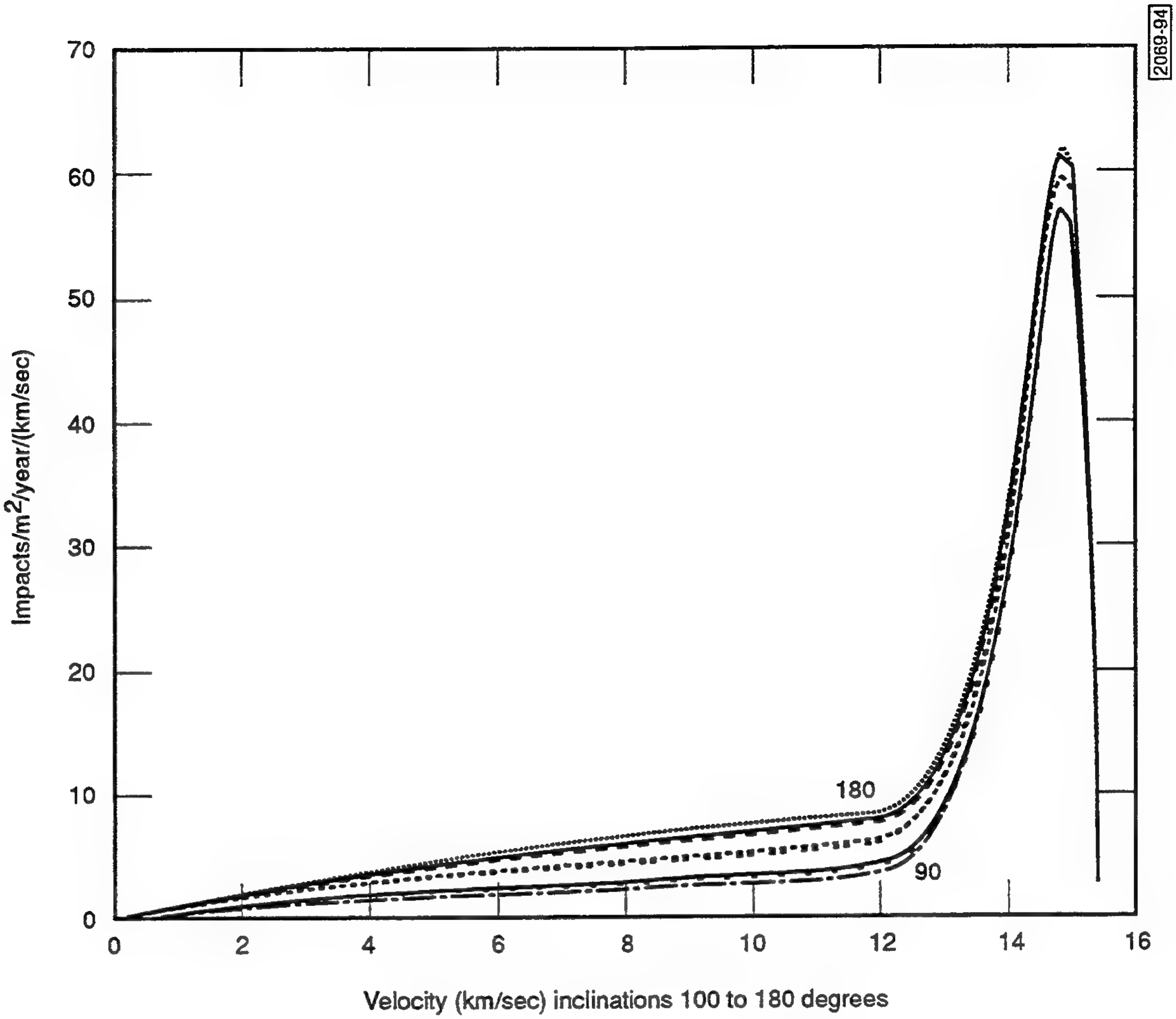

Figure 8. Kessler velocity function, f(v) (from Ref 13).

The original Kessler model was based on data from the United States Space Command (USSPACECOM) Catalog, results from the retrieved Solar Maximum Mission Satellite, and telescope data from the Air Force, NASA and MIT, and used assumed growth and collision frequency models. It was recently updated with the data obtained from LDEF. The model is limited in that radar and telescope data could not provide flux values at the smaller particle sizes, especially 1 μm to 1 cm, and that the only source of this data has come from retrieved satellites that inhabited limited altitude ranges. Although the model used the USSPACECOM Catalog data, its flux versus altitude curve does not agree with the catalog's above 700 km altitude. The curve as shown in Figure 5, becomes constant, while the catalog curve is irregular with peaks and valleys as shown in Figure 9, which summarizes the existing database for space debris.[7,13]

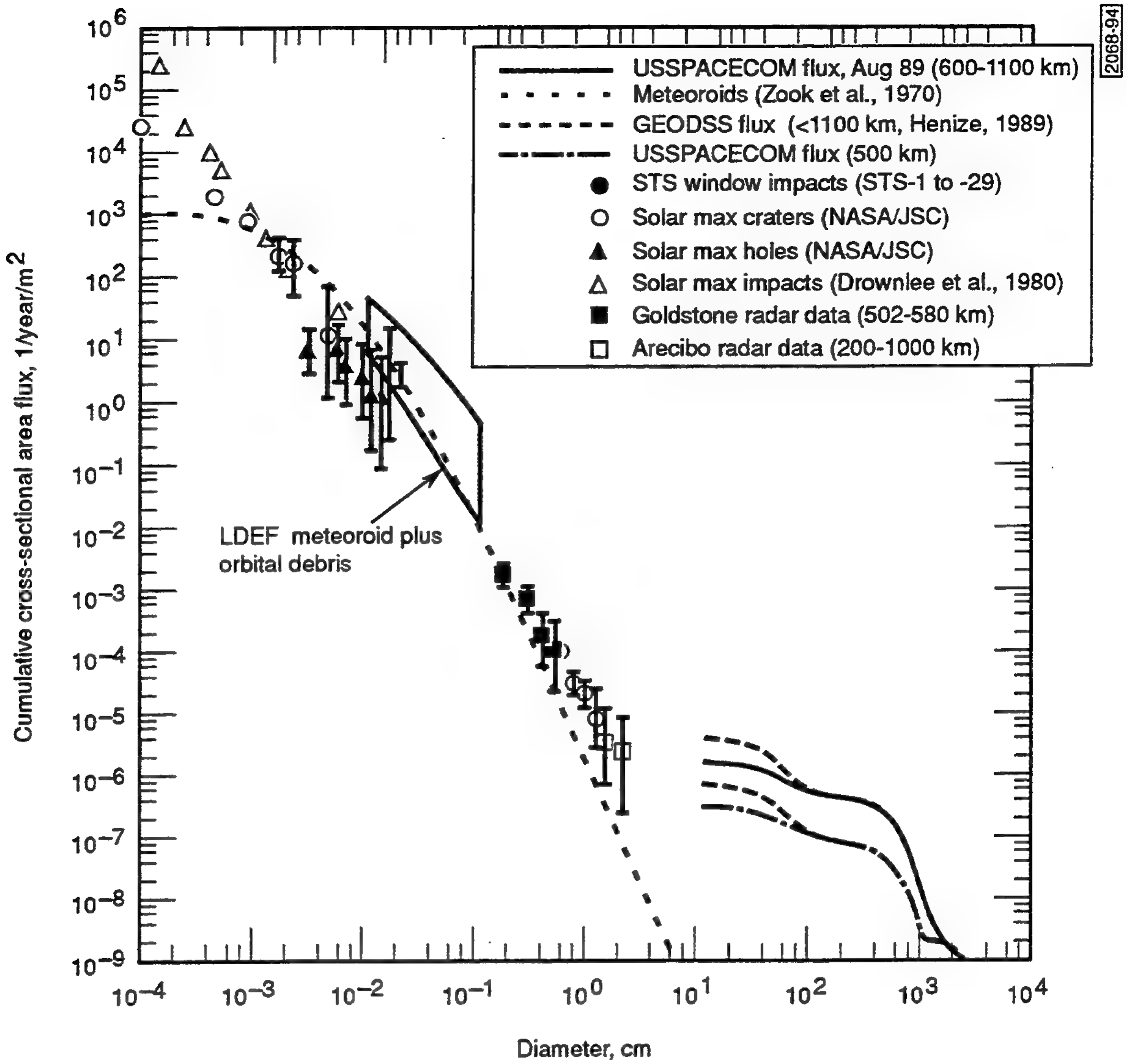

Figure 9. Existing database on space debris.

Recent Haystack radar surveys have indicated that the particle spread for 1 cm objects is not as great as the original model predicted, and Kessler has revised the model in view of this, as mentioned above. It is generally believed that the smaller particles produced by collisions and explosions move away from a fragmentation site with greater speed than the larger ones and are, therefore, more spread out across the altitudes. This behavior of being more spread out tends to cause the flux versus altitude curve for a given particle size to have a more constant distribution, which matches well with predictions of the model. Thus, the Kessler model may be fairly good for estimating small particle diameter fluxes.[7]

When bodies collide with each other, or fragment due to explosions, there is a fractal fragmentation log-log function describing the relative cumulative number of particles against the size of the

particles. Ground-based experiments using hypervelocity impact tests have confirmed that the general trend for the cumulative data as a function of the size of the resulting particles is very similar to that seen for space debris and meteoroids. Some of this data is shown in Figure 10. In all cases, the cumulative particle data tends to scale inversely with the size of the particle to some power. For debris collisions, this power index is at least 2.25, while the faster moving meteoroid collisions display a power index of up to 3.5.[6,13]

Kessler admits that the assumption of small particle spread may have been mis-modeled. Since the original model was published in 1989, Kessler has amended the estimated growth rates of the debris particles and the debris mass density assumptions and has increased the magnitudes of the mass distribution equations. All of these changes have been incorporated into the revised model presented above. *The uncertainty in the model has been guesstimated by Kessler to be approximately plus or minus three orders of magnitude for 1-mm particle sizes.* Several modifications to the Kessler model have been suggested by various organizations, but none addresses the mass

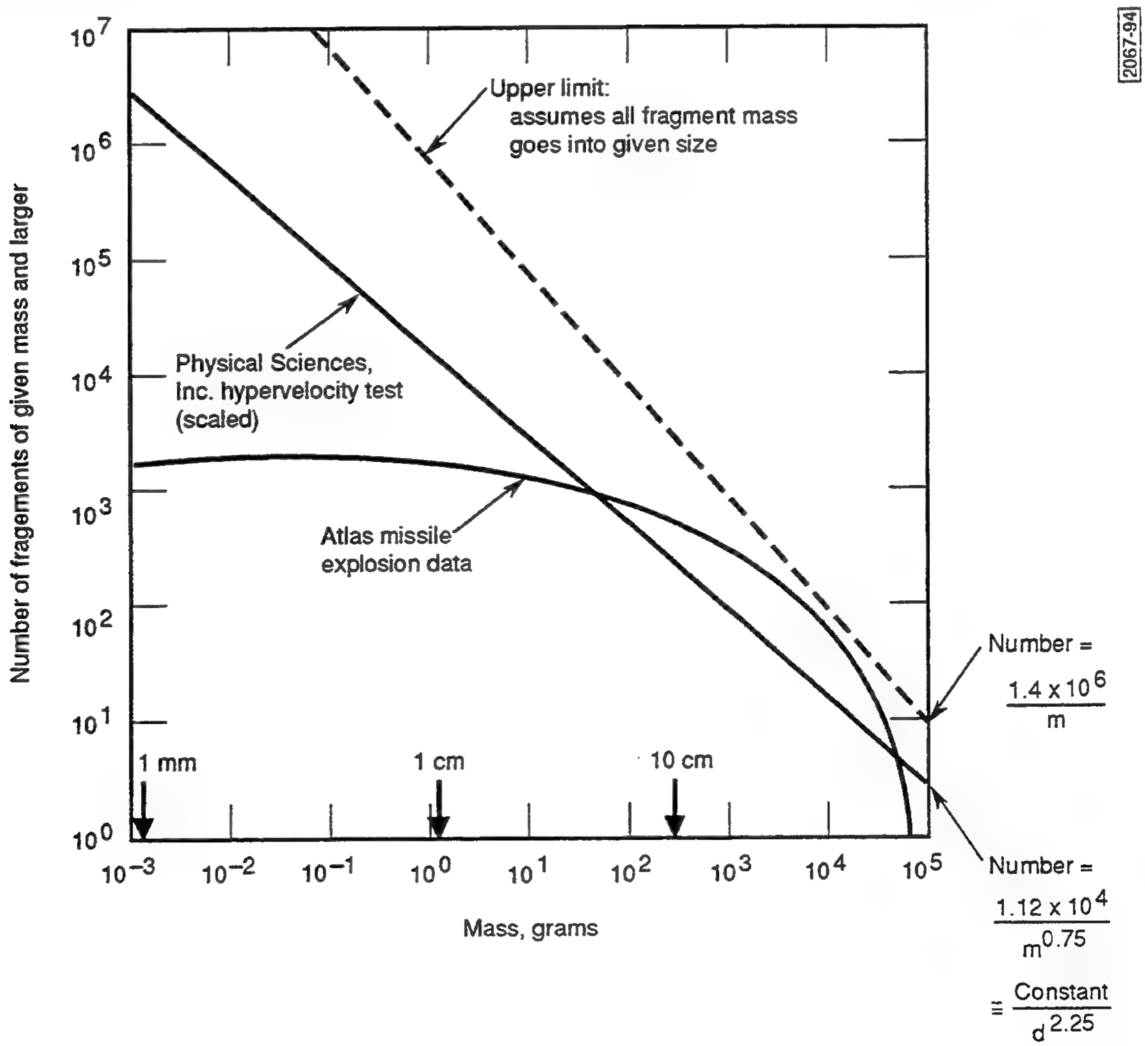

Figure 10. Expected number of fragments from the breakup of a 1400-kg satellite.

spread mis-modeling. It does not appear, at this time, to take any of these seriously since they do not alter the flux values significantly compared to the uncertainty in the model.[7]

Recent LDEF data suggests that the Kessler model may be more accurate than the above guesstimate. One of the difficulties in comparing data to the debris model is the presence of meteoroids. As Figures 1 and 2 indicate, the current models predict that natural meteoroids dominate in the 20 μm to 2 mm size range. Below 20 μm, the debris population strongly dominates. If impact data is compared to the sum of the Kessler debris and Cour-Palais meteoroid models, good correlation is observed, at least for ram surfaces.[13,14,15,16]

Caveats on the Kessler Model

Many caveats can be applied to the Kessler model, some of which have been briefly discussed above. The most significant limitation of the model derives from the fact that all debris orbits are presumed to be circular. In reality, most orbits are slightly or very elliptical. This causes inaccurate predictions for the impacts of space debris on the wake or trailing side of a spacecraft. Another limitation is that Kessler's velocity function is not intuitively obvious and appears to show a bias such that the distribution for a 0° orbit does not logically relate to the distribution for a 180° orbit, where the spacecraft velocity vector is merely inverted. Kessler's approach to solar-cycle atmospheric heating is also not rigorous. The model essentially applies a scalar multiplier based on the solar period. However, this results in an unrealistic effect. Scrutiny of Kessler's data in Figure 5, which shows the debris growth versus time and altitude, reveals that as the solar-cycle activity decreases, the amount of debris increases faster than it would have had there never been any atmosphere at all. Since the air drag can only slow particles down (thereby removing them from orbit), it is physically impossible for the debris to escalate in this manner. Thus, Kessler's model only provides a rough description of the debris flux versus time and altitude and is not based on a rigorous solution to the differential equations describing air drag on orbital characteristics.[13]

Kessler also gives no direct solution to the problem of self-collision increases in the small-particle population. For random debris orbits, the collision rate per volume per time is proportional to the square of the particle number density per volume, to the mean cross-sectional area, and to the mean collisional speed. Thus, the small-particle population should increase rapidly compared to that for the larger sizes. Kessler is fully aware of these implications and indicates that beyond a critical particle number density, a runaway situation occurs, with self-collisions causing the population to grow even without any further launches. Indeed, Kessler has suggested that this situation may have already occurred for debris at altitudes of 1,000 and 1,500 km, where the air drag effects are negligible and the debris population is high.[13]

Debris Clouds

While the Kessler debris model does an adequate job of predicting the number of debris encounters that will occur in a particular orbit, it is most useful for long-term, large-area predictions (impacts/m^2/year) and does not provide information regarding the spatial-temporal distribution of space debris within a short time interval. The Interplanetary Dust Experiment (IDE) on LDEF provided, for the first time, data that indicates that the debris environment is very "clumpy" and contains multi-orbit streams of particles that impact at rates orders of magnitude above the nor-

mal background fluxes.[17] This data has shattered the once-held notion that impacts occur on a spacecraft in LEO at a relatively constant rate and shown that conventional models are grossly inaccurate in their predictions of day-to-day fluxes of debris. A multi-orbit event sequence can only occur if the particulates themselves are in Earth orbit, intersecting the LDEF orbit. Each time that the LDEF came back into the same place in its orbit, it would encounter the same cloud again. A very strong stream of this type was seen on June 4, 1984, where the stream was seen every orbit for about 25 orbits at intensities up to 3 orders of magnitude above the average flux. The only reasonable assumption was that LDEF was passing through the orbital plane of some debris cloud associated with some (as yet unidentified) satellite. The same debris cloud was re-encountered some 54 days later after a complete precession of the LDEF orbit around the Earth had occurred. Evidently, debris clouds do not dissipate into the background as fast as one might expect. Similarly, the impact rate was elevated during the first eight days of the LDEF mission from the "Shuttle Induced Atmosphere," and the evidence is that spacecraft, especially the Shuttle, produce their own extremely dirty local environment. Multi-orbit event sequences comprise the major portion of the IDE data taken over the period of 346 days.

The IDE measured impact fluxes on the six orthogonal separate faces of LDEF. The sensors measured impacts due to particles greater than roughly 0.2 μm and up to 100 μm in diameter. From the data, there is no way to differentiate between debris and micrometeoroid impacts. However, the vast majority (> 80%) of the particle impacts are presumed to be from debris since the impactors must have been in the 25-μm and below range, where debris clearly dominates. Some of this time-resolved data is shown in Figure 11, graphically illustrating the clumpy nature of the debris encounters. This data indicates that the debris environment is highly variable from

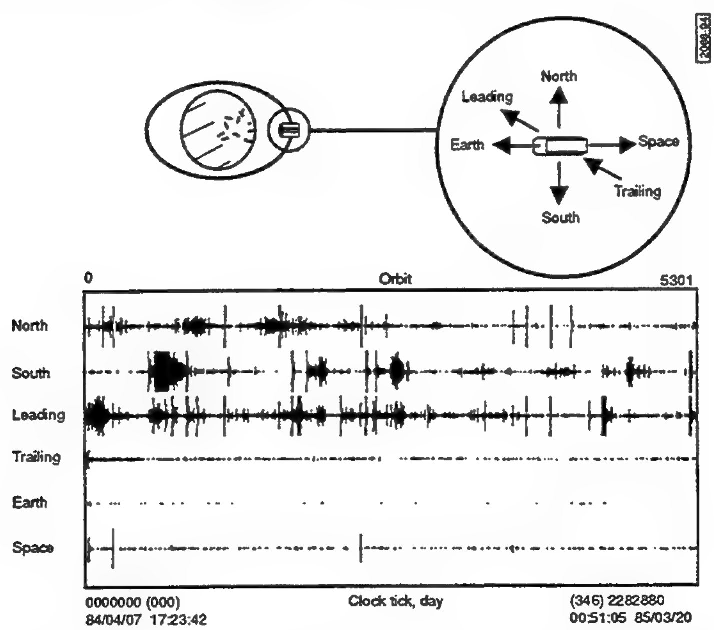

Figure 11. Time history of impacts on the 0.4 μm panels over the entire 346 day period of active IDE data recording. In this "seismograph" plot, the vertical extent of each trace indicates the impact rate as a function of time. The display has been truncated in the vertical direction in the most active portions to avoid overlap between adjacent traces (from Ref. 17).

minute to minute, hour to hour, and week to week. The analysis of the vast amount of data from this experiment is continuing.

Table 1 presents selected cumulative microparticle impact fluxes measured by various LDEF experimenters, including the sets of data obtained by the IDE.[18] It is important to note in this summary of data that there are different time periods for the various data sets, which correspond to the data collection times during the LDEF mission. From this data, it is apparent that there is good agreement among the three experiments for the integrated 5.77 year fluxes. While the IDE integrated fluxes for five of the six locations on LDEF varied by factors 0.5 to 8.3 depending on the data set, the fluxes for the leading edge or ram direction are essentially constant.

One of the more intriguing aspects of the IDE data comes from the Earth-facing side. which was originally considered to be the least interesting since it was presumed that it would be largely shielded from impacts. In reality, as the data in Table 1 indicates, the flux of impacts on the Earth end was comparable to that observed for the ram direction. Unlike the other five locations of the IDE detectors, where the long-term flux was less than the first year (346 day) flux, the Earth-end location measured a long-term impact flux that was roughly twice that of the first year. One hypothesis for this unexpected result states that the data has been skewed by a single event

Table 1. Selected Cumulative Microparticle Impact Fluxes Observed on LDEF Surfaces for Indicated Equivalent Crater Diameters in Aluminum. IDE data is for impacts that would produce craters in aluminum ≥ 3 µm in dia. FRECOPA data are for impacts into Al foils or plates with indicated crater sizes counted in SEM scans. MAP data are optical transmission counts of penetrations in thin foils with indicated equivalent crater sizes. Values in [ ] are subject to confirmation. Error estimates, s, are calculated from Poisson statistics; $s = (n^{-1/2})(f)$, where n is the number of impacts in the data set, and f is the flux.

	Impact Surface								
	Time Res.	Foil	Integrated	Integrated	Plate	2.0-µm Foil	3.1-µm Foil	3.7-µm Foil	4.8-µm Foil
	Data Type								
	IDE	FRECOPA	IDE	IDE	FRECOPA	MAP	MAP	MAP	MAP
	Crater Size (µm)								
	≥3	≥2	≥3	≥3	≥3	≥3	≥4	≥5	≥7
	Exposure Period (days of mission)								
LDEF Location	1–346	10–280	347–2106	1–2106 (5.77 yr)					
North (row 12)	6.1 ±0.18		3.5 ±0.20	3.9 ±0.17		[3.7] [±0.19]		[1.5] [±0.087]	1.3 ±0.060
South (row 6)	6.6 ± 0.19		3.2 ±0.19	3.8 ±3.19		[6.0] [±0.18	[2.2] [±0.15	[1.9] [±0.14	1.5 ±0.063
East Leading (row 9)	8.5 ±0.22		8.7 ±0.31	8.7 ±0.28					2.3 ±0.22
West Trailing (row 3)	0.99 ±0.073	0.86 ±0.38	0.12 ±0.013	0.26 ±0.016	0.22 ±0.11		[0.23] [± 0.049]	[0.062] [± 0.025]	0.070 ±0.014
Space (up)	1.1 ±0.090		0.48 ±0.039	0.59 ±0.045					0.34 ±0.024
Earth (down)	0.16 ±0.030		0.30 ±0.023	0.28 ±0.022					
	(All fluxes x 10^{-4} m^{-2} s^{-1})								

after the first year of the LDEF deployment. Coincidentally, in a 1986 SDIO sponsored test, a Delta rocket vehicle launched its third stage into such an orbit as to collide with its own second stage at 3 km/s. The collision was at about 2,000 km altitude.[19] The resulting debris cloud is known to have a large outward component, and ground-based tests suggest strongly that the cloud had a high number density of µm-sized particles. Similarly, an ASAT weapon test on 13 September 1985 resulted in a collision of 7 km/s between the weapon and an 850 kg P78-1 satellite at about 500 km altitude, nearly the same as LDEF.[19] While no firm conclusions can be drawn, it would appear that LDEF has provided a mural for recording these events.

Elliptical Debris

Most of the man-made objects in LEO being tracked and cataloged by the USSPACECOM are in near-circular orbits. There are so few objects in elliptical orbits that models describing the directional properties of orbital debris generally assume that all orbits are circular. Such an assumption leads to the conclusion that orbital debris will not impact the trailing surfaces of spacecraft in circular orbits. However, objects in elliptical orbits, especially those with low inclinations, are more difficult to detect and catalog than objects in circular orbits. This is because objects in elliptical orbits spend a smaller fraction of their time at low altitudes where ground-based sensors can detect them, and there are fewer ground-based sensors appropriately located to detect objects in low-inclination orbits. Thus, the USSPACECOM catalog is not likely to be representative of various orbit classes of large objects. Moreover, the amount of elliptical-orbital debris in the catalog is likely to increase with decreasing orbital debris size. The orbital lifetime of small debris in circular orbits at low altitudes is much shorter than in elliptical orbits.

Data from LDEF and, in particular, The Chemistry of Micrometeoroids Experiment[20] indicates that a significant fraction of the impacts on the trailing edge of LDEF were the result of space debris impacts. The distribution and possible source of these impacts have been carefully modeled by Kessler using collision probability theory, impact scaling laws, and two sets of LDEF data[21] The results of this study indicate that the only possible orbits capable of producing the observed distribution of impacts and, in particular, the necessary number of impacts on the trailing edge of LDEF are highly elliptical, low-inclination orbits. Highly elliptical orbits have perigees below LDEF's altitude of roughly 475 km and apogees near geosynchronous orbit (GEO) or 36,000 km. This is the type of orbit that is most difficult for USSPACECOM to track and catalog. This group of orbits is characteristic of orbital transfer stages from LEO to GEO. When a satellite is placed into GEO, an upper-stage rocket is usually left in this type of orbit. The U. S. is mostly responsible for leaving orbital transfer stages in highly elliptical orbits with inclinations of 28.5°, and the European Space Agency (ESA) is responsible for leaving orbital transfer stages in highly elliptical orbits with inclinations near 7°. At least two of ESA's upper stages in this type of orbit are believed to have exploded[22]; a total of three fragments were cataloged from these two events. When the same upper stage exploded in a circular low Earth orbit with a high inclination, 488 fragments were cataloged. It is, therefore, not unreasonable to conclude that the catalog does not adequately represent the low-inclination, highly elliptical orbital-debris population. *Kessler's modeling of the data suggests that the debris population in these orbits must be at least a factor of 20 higher than the catalog lists.*

There have been 17 satellite breakups (mostly upper-stage explosions) in highly elliptical orbits with inclinations over 50°; an average of less than four fragments per breakup were cataloged.[22] A valid assumption might be that this population is also not equally represented by the catalog. Kessler's calculations also indicate that if the debris populations in all elliptical orbits are weighted by a factor of 30, the results are nearly identical to those obtained by weighting the low-inclination orbits only by 20.

Consequently, the ratio of the amount of small debris in highly elliptical, low-inclination orbits to the amount of small debris in other types of orbits must be at least 20 times the same ratio for the larger cataloged objects in order to be consistent with the LDEF data. If all elliptical orbits are equally not represented by the catalog, then the ratio for small debris must be 30 times the ratio for cataloged objects. A graph of Kessler's curve fit is shown in Figure 12.

Chemical Composition and Density

There has been much effort expended trying to determine the identity of impactors—whether they were space debris or micrometeoroids. The largest body of data comes again from LDEF where there were experiments almost totally dedicated to providing data on this question. Much

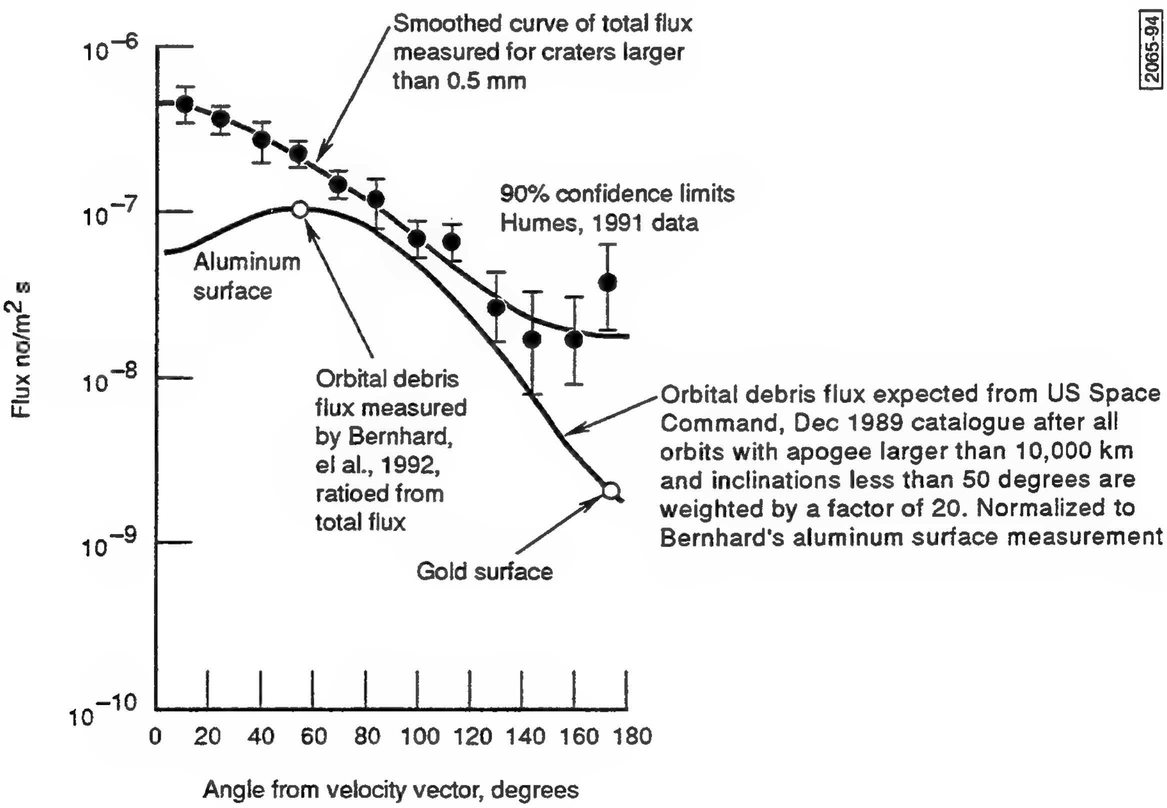

Figure 12. LDEF crater distribution expected from weighted highly elliptical, low-inclination orbits in U. S. Space Command catalog (from Ref. 20).

of the additional work in this area has been performed by members of the LDEF Meteoroid and Debris Special Investigation Group (M & D SIG).[3]

The best means for determining the origin of the impactor is through chemical analysis of impactor residue, if any can be found in the crater or entrained in a capture cell. If there is a large residue, energy dispersive analysis of X-rays (EDX) can be used to identify the elements present; however, more sensitive techniques are often required such as Secondary Ion Mass Spectroscopy (SIMS). In general, most spacecraft debris particles consist of aluminum fragments of spacecraft structures, aluminum oxide from the burning of solid rocket motors, or zinc oxide, titanium oxide, or aluminum oxide from paint pigments. There also is a sizable component due to human waste, which is characterized by containing the elements phosphorus, sodium, and potassium.

The M & D SIG[3] has put forth the following chemical criteria for distinguishing between natural and man-made impactors:

Chemical Criteria for Natural Impactors:

1. Mainly Fe with minor S and/or Ni
2. Various proportions of Mg, Fe, and Ca with minor S, Ni, and/or Al
3. Fe and Cr only if O is present in same residue grains
4. Non-terrestrial isotopic compositions
5. Presence of solar-wind-implanted He or Ne

Chemical Criteria for Man-made Impactors:

1 Mainly Al or Al_2O_3 with minor Fe, Ni, Cr, Cl, Na, or C
2. Mainly Fe with accessory Cd, Ti, V, Cr, Ni, Mn, Co, Cu, or Zn, with the latter elements present in abundances greater than in common minerals
3. Various proportions of Ca, Al, Si, Ti, K, Zn, Co, Sn, Pb, Cu, S, Cl, Au, or Ag

These criteria provide a fairly good estimate of the elements that are likely to make up space debris. Particles that are Fe-Ni-Cr rich are representative of stainless steel, while Ag- and Cu-containing particles represent electronic materials.

The actual knowledge of debris shape and density is fairly scant. Actual shapes are irregular and include flat plates, rods, hollow structures, and crumpled metal. As size decreases, the objects tend

to be somewhat less irregular. With regard to the density of debris, the present recommendation is that for particles smaller than 0.62 cm, the mean density should be set at 4.7 g/cm^3. This is based on the fact that most of these smaller particles consist of alumina generated from solid rocket motors, or titania and zinc oxide, which are the debris from thermal control paints and coatings. For larger particles, greater than 0.62 cm, the mean density is initially about 2.8 g/cm^3, representing aluminum, but decreases as the size of the particle or object increases. An empirical relationship is:

$$\rho = 2.8\, d^{-0.74},$$

where ρ is in g/cm^3, and the diameter, d, is in cm. The basic explanation for this is that the objects are not solid bodies, but rather are portions of structures and, therefore, are partially hollow or pseudo-porous. This relationship is based on observed breakups, area-to-mass calculations derived from atmospheric drag, ground fragmentation tests, and known intact satellite characteristics.

Summary

There is a component of the space environment that is man-made pollution, termed "space debris;" it exists at all inclinations and primarily at altitudes of roughly 350 km to 2,000 km. The size of this debris ranges from several meters to a fraction of a micrometer in diameter, and the particle distribution follows an inverse power law with the smaller-size component far exceeding that of the larger. Debris is composed primarily of alumina from solid rocket motor exhausts, aluminum from spacecraft structures, and zinc and titanium oxides from thermal control coatings. The accepted model of the space debris environment is that of Kessler et al. It is a complex model that predicts the number of particles that will impact a surface as a function of altitude, inclination, solar cycle, and particle diameter, as well as their collision velocities. Recent data from LDEF has demonstrated both the accuracy and shortcomings of the Kessler model.

Measured debris impactor fluxes are in good agreement with the model for ram surfaces. However, predictions of the model for other surfaces of a spacecraft are less accurate, most notably for the wake or trailing side. While the Kessler model is appropriate for long-term, average flux predictions, spatial-temporal impact fluxes measured on LDEF dramatically illustrated the presence of strong debris clouds that do not dissipate quickly in space and will encounter an orbiting spacecraft cyclically and repeatedly over its lifetime. LDEF data has also indicated the presence of debris in elliptical orbits, a fact not predicted by the Kessler model and responsible for the discrepancy between measured impact fluxes and predictions on trailing-edge surfaces.

Production and orbital accumulation of this man-made pollution, space debris, has accelerated due to the steadily increasing numbers of launches by industrialized countries. There is a growing concern and awareness that this problem must be addressed. In addition to the obvious issue of Earth impact, resulting in loss of life and/or property damage, more insidious damage could result from depletion of stratospheric ozone. This possibility needs to be studied further and modeled if possible.

As other countries become more industrialized and more active in space, or if systems such as those envisioned under SDI are tested or deployed in space, it becomes obvious that future spacecraft will have to be designed for a real and serious ballistic threat. This will require a considerable weight penalty. It may be that for spacecraft in low to medium Earth orbits, serious design changes will be required by the year 2000. In addition to this obvious collisional threat, accumulation of space debris can be expected to impede the ability of a space system to perform its mission, whether it is surveillance or communication. If the natural resource that is space is to be preserved, then space debris must be controlled.

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